Dopaminergic Haplotype as a Predictor of Spatial Inattention in Children With Attention-Deficit/Hyperactivity Disorder

Mark A. Bellgrove, PhD; Katherine A. Johnson, PhD; Edwina Barry, MD; Aisling Mulligan, MD; Ziarah Hawi, PhD; Michael Gill, PhD; Ian Robertson, PhD; Christopher D. Chambers, PhD

Context: A distinct pattern of selective attention deficits in attention-deficit/hyperactivity disorder (ADHD) has been difficult to identify. Heterogeneity may reflect differences in underlying genetics.

Objective: To document an objective deficit of selective attention in a large sample of children with and without ADHD using spatial orienting paradigms. By stratifying samples according to the gene dosage of a risk haplotype of the dopamine transporter gene (DAT1), we could determine whether genetic factors predict spatial inattention in ADHD.

Design: A case-control design was used.

Setting: Children with ADHD were recruited from clinics or support groups in Ireland. Typically developing children were recruited from schools in and around Dublin, Ireland.

Participants: One hundred fifteen children were recruited (ADHD=50, control=65). Groups were matched for age but differed in estimated intelligence.

Intervention: Two versions of a visual spatial orienting task in which attention was directed by valid, neutral, or invalid cues to target locations. Sudden-onset peripheral cues (exogenous) and centrally presented predictive cues (endogenous) were used.

Main Outcome Measures: To isolate an attention deficit in ADHD, groups were first compared using analysis of variance on the spatial orienting tasks. Multiple regression was used to assess the main effect of DAT1 haplotype status (heterozygous vs homozygous) and the interaction of diagnosis and genotype on those variables that discriminated children with and without ADHD.

Results: Children with ADHD displayed deficits in reorienting attention from invalidly cued spatial locations, particularly for targets in the left visual field. DAT1 haplotype status predicted spatial reorienting deficits for left visual field targets (P=0.007) but there was also a significant interaction of diagnosis and genotype (P=0.02), which revealed the greatest impairment in children with ADHD homozygous for the DAT1 haplotype.

Conclusion: Heterogeneity in selective attention in ADHD can be explained by a replicated genetic risk factor for ADHD, the 10/3 DAT1 haplotype.

Arch Gen Psychiatry. 2009;66(10):1135-1142
tive of spatial selection. First, when attention is cued validly to a target location, RTs are typically faster than when the target is preceded by a neutral cue. This RT benefit reflects the attentional enhancement of perceptual processing at validly cued locations. In contrast, the disadvantage or cost in RT conferred by invalid cues, relative to either neutral or valid cues, reflects the time taken to reorient attention from the invalidly cued location to detect a target in an uncued location. Additionally, 2 modes of visual orienting can be distinguished. Stimulus-driven or exogenous mechanisms can be probed using salient peripheral cues that capture attention. In contrast, strategic or endogenous mechanisms can be probed by building expectancy across trials using a centrally presented stimulus (eg, arrowhead) that cues attention on most occasions.

Human lesion, neurodisruption, and functional imaging work have helped to define the neural substrates of spatial orienting and reorienting. Broadly speaking, tasks in which attention is strategically allocated to a spatial location activate a bilateral network of brain regions that has been conceptualized as forming a dorsal frontoparietal network. This network is thought to comprise the frontal eye fields and the dorsal posterior parietal cortex along the intraparietal sulcus. Activation foci in the basal ganglia and cerebellum have also been observed for endogenous orienting. This bilateral dorsal frontoparietal network may be contrasted with a right-lateralized ventral frontoparietal network that includes the inferior frontal gyrus and temporoparietal junction. Classically, patients with lesions to the right parietal lobe have difficulty reorienting their attention from invalidly cued locations in the right hemifield to detect targets in the left hemifield. That is, these patients display an ipsilesional orienting bias and contralesional reorienting deficit.

Several lines of evidence suggest dopaminergic modulation of spatial attention. First, dopamine agonists modulate behavioral indexes of visual spatial orienting in healthy subjects and reduce the extent of neglect in right-hemisphere patients. Second, experimental lesions of ascending dopaminergic pathways in rodents induce a spatial neglect for the contralateral side. Deficits in spatial orienting and attentional biases have also been observed in patients with Parkinson disease, particularly those with greater dopamine loss in the right striatum.

A number of studies have now applied spatial orienting tasks to the study of selective attention in ADHD. Although the results from these studies have proven inconclusive, a number of studies have noted asymmetrical performance of the participants with ADHD, such that they performed more poorly than controls in one visual field. Epstein et al noted increased cueing costs for left visual field targets in ADHD. Nigg et al and McDonald et al noted slowed responses in the left visual field for uncued targets. Increased cueing costs for left targets may be indicative of a right-hemisphere reorienting deficit whereas slowed responses to uncued left targets could reflect a right-hemisphere arousal deficit. Studies using other selective attention paradigms have also described left-sided impairments. Nevertheless, a number of studies using visual orienting tasks have either failed to document group differences, observed reduced rather than increased costs for left targets, or observed increased costs for right targets.

Inconsistencies between studies likely reflect differences in methods but also the well-documented neuropsychological heterogeneity of ADHD. Herein, we sought to determine whether inconsistencies could be clarified by stratifying children according the presence of a frequent haplotype of the dopamine transporter gene (DAT1). Allelic variation in DAT1 is a replicated genetic risk factor for ADHD, and a common haplotype comprising the 10-repeat and 3-repeat alleles of 2 variable number of tandem repeat polymorphisms (VNTRs) within this gene is thought to increase risk for the disorder. No studies have yet established the functional significance of this haplotype for cognition in ADHD. In a previous report, we demonstrated an influence of DNA variants of DAT1 on exogenous spatial attention in healthy control children. If neuropsychological heterogeneity in ADHD reflects differences in underlying genetics, then spatial attention deficits, including the reorienting of attention between the visual fields, should be most pronounced in those children with ADHD with a higher gene dosage of the DAT1 haplotype.

METHODS

PARTICIPANTS

One hundred fifteen children participated in this study (ADHD=50, control=65). Clinical and demographic data can be found in Table 1. Data from 51 healthy control children on the exogenous orienting task have been presented previously. Children with ADHD were referred by psychiatrists or recruited via support groups in Ireland. A subset of the ADHD group had previously participated in studies linking variation in DAT1 to clinical measures of spatial bias (eg, line bisection). All participants with ADHD met DSM-IV diagnoses for ADHD, as determined through semistructured interviews by psychiatrists using the parent form of the Child and Adolescent Psychiatric Assessment or the Parental Account of Childhood Symptoms. Forty-four (88%) of the children met criteria for ADHD predominantly combined type and 6 (14%), for ADHD predominantly inattentive type. The frequency of oppositional defiant disorder was 32% and conduct disorder, 8%. Exclusion criteria included known neurological conditions or pervasive developmental disorders, serious head injuries, and lower than average intelligence (<70 on a short form of the Wechsler Intelligence Scale for Children III that included Block Design, Information, Picture Completion, and Vocabulary). Control children were also excluded if they had first-degree relatives with ADHD. Handedness was measured using the Edinburgh Handedness Inventory.

The parents of all children also completed the Conners’ ADHD Rating Scale–Revised: Long or Short versions at the time of cognitive testing. Control children had Conners’ Global Index t scores of 60 or less. To facilitate the inclusion of as many participants with ADHD as possible, we did not apply an inclusion cutoff for Conners’ ratings (eg, t>65). Nevertheless, the majority of the participants had Conners’ Global Index t scores of 65 or more (n=43) and 7 had Global Index t scores less than 65 (range across ADHD cohort, 52-90). Given robust evidence for an association between reading disorder and spatial attention impairment, participants scoring in the clinical range (t>1.5 SDs lower than the mean of the reading sub-
SPATIAL ORIENTING TASKS

Participants performed both an exogenous and endogenous reflexive orienting task across separate sessions, each lasting approximately 1.5 hours (Figure 1). In both tasks, participants used a joystick to indicate whether a target stimulus appeared at an upper (forward response) or lower (backward response) location of the visual field. Participants identified the vertical location of the target (upper or lower) as rapidly as possible using a joystick, irrespective of whether the target occurred on the left or right. This orthogonal cuing procedure enables mechanisms of spatial attention to be assessed independently of any potentially confounding effects of response selection or response bias.34 Stimulus onset asynchronies were randomly either 200 or 800 milliseconds for the exogenous task and 500 or 700 milliseconds for the endogenous task.

The stimulus onset asynchrony (SOA) between the cue and target was randomly either 200 or 800 milliseconds for the exogenous task and 500 or 700 milliseconds. Participants performed 320 trials. Both tasks were performed in a counterbalanced order, with eye movements monitored on a trial-by-trial basis. Trials on which a saccade occurred were excluded from analysis.

GENOTYPING

Genomic DNA was extracted from blood or saliva using Oragene DNA Self-Collection Kits (DNA Genotek Inc, Ottawa, Ontario, Canada). Polymerase chain reaction amplification of the intron 8 marker was performed as described in our previous report.27 Polymerase chain reaction amplification and genotyping of the 3′ untranslated region (UTR) VNTR was conducted, and results were analyzed.

Table 1. Clinical and Demographic Data for the ADHD and Control Participants

<table>
<thead>
<tr>
<th></th>
<th>ADHD (n=50)</th>
<th>Controls (n=65)</th>
<th>Significance Test</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male, No.</td>
<td>42</td>
<td>61</td>
<td>χ² = 0.3</td>
<td>.57</td>
</tr>
<tr>
<td>Right-handed, No.</td>
<td>44</td>
<td>57</td>
<td>χ² = 1.9</td>
<td>.37</td>
</tr>
<tr>
<td>Age, y</td>
<td>13.3 (1.7)</td>
<td>13.7 (2)</td>
<td>t₁₁ = 1.1</td>
<td>&gt;.05</td>
</tr>
<tr>
<td>IQ</td>
<td>99 (13)</td>
<td>111 (13)</td>
<td>t₁₁ = 4.9</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>WRAT reading score</td>
<td>96 (12)</td>
<td>108 (13)</td>
<td>t₁₁ = 5.3</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>WRAT spelling score</td>
<td>93 (13)</td>
<td>108 (14)</td>
<td>t₁₁ = 5.9</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Conners’ ADHD Index score</td>
<td>74 (8)</td>
<td>45 (7)</td>
<td>t₁₁ = 20.8</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Conners’ Global Index score</td>
<td>77 (10)</td>
<td>46 (5)</td>
<td>t₁₁ = 21.5</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Conners’ DSM-IV Inattentive score</td>
<td>73 (9)</td>
<td>45 (7)</td>
<td>t₁₁ = 18.9</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Conners’ DSM-IV Hyperactive/Impulsive score</td>
<td>79 (12)</td>
<td>47 (5)</td>
<td>t₁₁ = 20.1</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Conners’ DSM-IV Total score</td>
<td>78 (9)</td>
<td>46 (6)</td>
<td>t₁₁ = 22.8</td>
<td>&lt;.05</td>
</tr>
</tbody>
</table>

Table 2. Medication History for the Participants With ADHD

<table>
<thead>
<tr>
<th>Type of Medication</th>
<th>No. of Children With ADHD Medicated</th>
<th>Medication Dose, mg, Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concerta</td>
<td>15</td>
<td>18-72</td>
</tr>
<tr>
<td>Ritalin</td>
<td>6</td>
<td>10-30</td>
</tr>
<tr>
<td>Ritalin SR</td>
<td>3</td>
<td>30-40</td>
</tr>
<tr>
<td>Strattera</td>
<td>1</td>
<td>NA</td>
</tr>
<tr>
<td>Dexamethone</td>
<td>1</td>
<td>7.5</td>
</tr>
<tr>
<td>Concerta and risperidone</td>
<td>1</td>
<td>72 and 1</td>
</tr>
<tr>
<td>Previously but not currently medicated</td>
<td>9</td>
<td>. . .</td>
</tr>
<tr>
<td>Never medicated</td>
<td>14</td>
<td>. . .</td>
</tr>
</tbody>
</table>

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; ellipses, not applicable; NA, not available; SR, slow release.

Spatial cue and 20% were invalid. To reduce the temporal predictability of each trial, the cue-target SOA was randomly either 500 or 700 milliseconds. Participants performed 320 trials. Both tasks were performed in a counterbalanced order, with eye movements monitored on a trial-by-trial basis. Trials on which a saccade occurred were excluded from analysis.

Figure 1. Task schematics of the exogenous (A) and endogenous (B) covert visual orienting paradigms. In both tasks, participants fixated on a central point (500-millisecond duration) that turned from gray to yellow to signal the commencement of a trial. Each display included 4 black placeholders (2.1° diameter) that were positioned 13.3° to the left or right and 3.6° above and below fixation. Thereafter, attention was cued exogenously via a luminance increase in the peripheral placeholders (100 milliseconds; 100% contrast) or endogenously via predictive arrowheads presented above and below fixation (300 milliseconds). The target stimulus was a 100-millisecond sine-wave grating that occurred with equal probability within the upper or lower placeholder of the left or right visual field. Participants identified the vertical location of the target (upper or lower) as rapidly as possible using a joystick, irrespective of whether the target occurred on the left or right. This orthogonal cuing procedure enables mechanisms of spatial attention to be assessed independently of any potentially confounding effects of response selection or response bias.34 Stimulus onset asynchronies were randomly either 200 or 800 milliseconds for the exogenous task and 500 or 700 milliseconds for the endogenous task.

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; WRAT, Wide Range Achievement Test.
RESULTS

CHILDREN WITH ADHD DISPLAY SPATIAL ATTENTION DEFICITS

Exogenous Cuing Effects

RT: 200-Millisecond SOA. Reaction time data were submitted to a diagnosis × side × cue ANOVA, with IQ covaried. Significance levels for analyses without IQ covared are also presented for comparison purposes for key effects. A significant main effect of diagnosis (F1,112 = 29.9; P < .001) was observed, which reflected slower RTs of the children with ADHD (mean [SE], 588 [14] milliseconds) compared with controls (mean [SE], 486 [12] milliseconds). There was a significant main effect of target side (F1,112 = 5.02; P = .03), which reflected slower responses to targets in the left visual field (mean [SE], 540 [9] milliseconds) relative to targets on the right (mean [SE], 533 [8] milliseconds). There was also a significant main effect of cue (F2,224 = 4.595; P = .01). Responses on invalid trials (mean [SE], 544 [9] milliseconds) were slower than on neutral trials (mean [SE], 529 [8] milliseconds; P < .001) and tended to be slower than on valid trials (mean [SE], 538 [9] milliseconds; P = .09). Valid trials were slower than neutral trials (P < .008). The slower responses to invalid, relative to neutral, cues permitted the calculation of cuing costs. Since responses to valid trials were slower than to neutral trials, cuing “benefits” must be interpreted with caution.

A significant interaction was observed between diagnosis, target side, and cue (F2,224 = 3.06; P < .05). This effect was also significant without IQ covaried (P < .05). As shown in Figure 2, children with ADHD exhibited significantly higher cuing costs for left targets than did control children (F1,112 = 5.4; P < .05); however, cuing costs did not differ for right targets (F1,112 = 0.39; P = .54). Cuing benefits for right targets differed between the groups (F1,112 = 5.034; P = .03), being positive for the ADHD group and negative for the control children. A negative cuing benefit for the control children indicates that, on average, the control children did not accrue a performance benefit from valid spatial cues. There were no differences in cuing benefits for left targets (F1,112 = 0.63; P = .43). The earlier-mentioned effects for cuing benefits were driven by asymmetrical responses in the ADHD group to validly cued trials (F1,112 = 5.76; P = .02); Children with ADHD responded more slowly to validly cued left, relative to right, targets (P = .001), whereas no such asymmetry existed for control children (P = .30). Neither the children with ADHD nor control children displayed asymmetrical responses to neutrally cued trials (F1,112 = 0.89; P > .05).

RT: 800-Millisecond SOA. At the 800-millisecond SOA, there was no main effect of cue (F2,224 = 0.016; P = .98). There

STATISTICAL ANALYSES

A 2-step approach to statistical analysis was undertaken. First, we sought to confirm a spatial attention deficit in the ADHD group, relative to controls, independent of genetic effects. Reaction time data were submitted to mixed-model analyses of variance (ANOVAs), with task factors as repeated measures and diagnosis as a between-subjects factor. The benefit of valid spatial cues for perception was assessed relative to neutrally cued trials (benefits). The cost to perception of invalid spatial cues was assessed relative to both a valid (validity effect) and neutral cue baseline (costs). Preliminary analyses showed no interactions between diagnosis and critical task factors for error rates or variability of RT. We therefore present mean RT results for correct responses only. Because cuing effects at the short and longer SOAs in the exogenous paradigm may not be directly comparable, we analyzed mean RT at each SOA separately. Although the SOA manipulation in the endogenous cuing paradigm was primarily designed to provide temporal jitter, SOA was nonetheless analyzed as a factor. Because cuing costs typically increase with SOA in endogenous cuing tasks, the longer SOA might provide greater sensitivity to detect group differences than the shorter SOA. Second, we sought to determine the relationship between DAT1 genotype and those specific cognitive indexes that discriminated children with ADHD and controls, thus reducing the potential for type 1 error. Multiple regression determined whether DAT1 10/3 haplotype status (2 copies vs <2 copies) accounted for unique variance in attentional indexes over and above that attributed to IQ and diagnosis. The interaction term (diagnosis × DAT1 haplotype status) was included to determine whether deficits were particularly pronounced in the subset of children with ADHD who were homozygous for the 10/3 haplotype. Although geno-

duced as described by Cook et al. Genotypes within the ADHD and control cohorts across each of the 3’ UTR and intron 8 VNTRs were in Hardy-Weinberg equilibrium (ADHD: 3’ UTR, χ² = 0.35; P > .05; intron 8, χ² = 0.03; P > .05; control: 3’ UTR, χ² = 1.77; P > .05; intron 8, χ² = 0.05; P > .05). Linkage disequilibrium between the 2 markers was calculated in the control sample as (D’) 0.77.

DAT1 10/3 haplotype status was assigned to participants using a Bayesian approach to reconstructing haplotypes implemented in the program PHASE version 2.02. Haplotypes were determined for 84 participants (31 ADHD; 53 control; probability ≥ 0.9). Sixteen (33%) of the participants with ADHD were homozygous for the 10/3 haplotype, whereas 14 (45%) were heterozygous. One participant with ADHD did not possess the 10/3 haplotype. Sixteen (30%) of the healthy control children were homozygous and 29 (55%) were heterozygous for the 10/3 haplotype. Eight control children (16%) did not possess the 10/3 haplotype. For statistical analysis, participants were grouped as possessing two 10/3 haplotypes or fewer than two 10/3 haplotypes. A χ² analysis confirmed a significant association between DAT1 10/3 haplotype status and diagnosis (χ² = 4.69; P = .03; odds ratio, 1.79 [95% confidence limit, 1.06, 3.02]). The frequency of the 10/3 DAT1 haplotype was 76% and 65% within ADHD and control cohorts, respectively. There was no influence of 10/3 haplotype status on IQ in children with ADHD (F1,30 = 0.007; P > .05) or typically developing children (F1,83 = 1.18; P > .05). Nor was there an interaction between diagnost and DAT1 genotype for IQ (F1,83 = 0.37; P > .05). Increasing gene dosage of the 10/3 haplotype was associated with increasing symptoms (r = 0.84; Conners’ DSM-IV Inattention: r = 0.27; P = .01; Conners’ DSM-IV Total: r = 0.25; P = .02; Conners’ ADHD Index: r = 0.28; P = .01). The direction of these effects was consistent in both children with and without ADHD.
was, however, a main effect of diagnosis \((F_{1,112}=27.5; P=.001)\) and a diagnosis \(\times\) cue interaction \((F_{1,224}=5.26; P=.006)\), which reflected a greater effect of cues in the children with ADHD than controls \((P=.002 \text{ without IQ covaried})\). Cuing costs were higher in the ADHD group \((\text{mean [SE]}, 14 [3] \text{ milliseconds})\) than in controls \((\text{mean [SE]}, 3 [3] \text{ milliseconds})\) \((F_{1,112}=6.07; P<.02)\), as was the validity effect \((\text{invalid RT}−\text{valid RT})\) \((\text{ADHD: mean [SE]}, 12 [4] \text{ milliseconds}; \text{controls: mean [SE]}, −5 [4] \text{ milliseconds})\) \((F_{1,112}=8.433; P<.005)\). The results for the control children at the 800-millisecond SOA were as expected: at a longer cue-target delay, attention shifts away from the cued location, resulting in less cost to perception of invalid cues.\(^{38}\) In contrast, even at the longer SOA, children with ADHD demonstrated increased cuing costs and higher validity effects, suggesting that attention shifted from the cued location more slowly. Cuing costs and the validity effect correlated with each other \((r=0.47; P=.001)\), suggesting that both measures index a common spatial reorienting mechanism. There were no differences between the groups in terms of cuing benefits \((F_{1,112}=1.2; P>.05)\).

### Endogenous Cuing Effects: RT

Of the total sample of 115 children, data on the endogenous orienting task were available for 49 children with ADHD and 63 control children. Mean RT data were submitted to a diagnosis \(\times\) target side \(\times\) cue \(\times\) SOA mixed-model ANOVA. In addition to a main effect of diagnosis \((F_{1,109}=45.57; P<.001)\), there was a diagnosis \(\times\) target side \(\times\) cue interaction \((F_{2,218}=3.04; P=.05)\) \((P=.09 \text{ without IQ covaried})\). Costs, benefits, and the validity effect were calculated over SOA as a function of target side. There was a significant interaction between diagnosis and target side for the validity effect \((F_{1,109}=6.03; P=.02)\) \((P=.06 \text{ without IQ covaried})\) \((\text{Figure 3})\).

Children with ADHD had significantly higher validity effects at the 700-millisecond SOA \((\text{mean [SE]}, 47 [6] \text{ milliseconds})\), compared with controls \((\text{mean [SE]}, 27 [6] \text{ milliseconds})\) \((P=.03)\). Further, validity effects increased as a function of SOA in the ADHD group \((P=.002)\), but not in controls \((P=.73)\). This effect was driven by a significant interaction between diagnosis and SOA for invalid RTs \((F_{1,109}=5.58; P=.02)\), but not for valid RTs \((F_{1,109}=0.67; P>.05)\). Reaction time differences between children with ADHD and control children for invalid trials increased with SOA as a result of an increase in RT for the children with ADHD, and a decrease in RT for control children, over SOA.

Taken together, compared with validly cued trials, the children with ADHD were slower to reorient attention to targets in the left, relative to right, visual field and showed increased validity effects for left targets than control children. Irrespective of lateral effects, group differences in invalid RT were maximal at the longer SOA.

**DOPAMINERGIC HAPLOTYPE PREDICTS SPATIAL INATTENTION IN ADHD**

### Exogenous Cuing Effects

**DAT1** 10/3 haplotype status accounted for significant variance in cuing costs for targets in the left, but not right, visual field at the 200-millisecond SOA (Table 3). Diagnosis and **DAT1** interacted: cuing costs for left visual field targets were highest in children with ADHD who were 10/3 haplotype homozygotes (Figure 4).

Although there was no association between **DAT1** 10/3 haplotype status and cuing costs at the 800-millisecond SOA mixed-model ANOVA. In addition to a main effect of diagnosis \((F_{1,109}=45.57; P<.001)\), there was a diagnosis \(\times\) target side \(\times\) cue interaction \((F_{2,218}=3.04; P=.05)\) \((P=.09 \text{ without IQ covaried})\). Costs, benefits, and the validity effect were calculated over SOA as a function of target side. There was a significant interaction between diagnosis and target side for the validity effect \((F_{1,109}=6.03; P=.02)\) \((P=.06 \text{ without IQ covaried})\) \((\text{Figure 3})\).

Children with ADHD had significantly higher validity effects at the 700-millisecond SOA \((\text{mean [SE]}, 47 [6] \text{ milliseconds})\), compared with controls \((\text{mean [SE]}, 27 [6] \text{ milliseconds})\) \((P=.03)\). Further, validity effects increased as a function of SOA in the ADHD group \((P=.002)\), but not in controls \((P=.73)\). This effect was driven by a significant interaction between diagnosis and SOA for invalid RTs \((F_{1,109}=5.58; P=.02)\), but not for valid RTs \((F_{1,109}=0.67; P>.05)\). Reaction time differences between children with ADHD and control children for invalid trials increased with SOA as a result of an increase in RT for the children with ADHD, and a decrease in RT for control children, over SOA.

Taken together, compared with validly cued trials, the children with ADHD were slower to reorient attention to targets in the left, relative to right, visual field and showed increased validity effects for left targets than control children. Irrespective of lateral effects, group differences in invalid RT were maximal at the longer SOA.
At the 500-millisecond SOA, there was neither a main effect of DAT1 haplotype status nor an interaction of DAT1 and diagnosis. At the 700-millisecond SOA, however, there was a significant interaction between DAT1 and diagnosis. Validity effects were highest in the children with ADHD who had a higher gene dosage of the 10/3 haplotype displayed pronounced deficits across measures but were particularly impaired in reorienting attention to detect targets in the left visual field at short (200-millisecond) SOAs. Our results provide the first evidence, to our knowledge, that a frequent (10/3) haplotype of DAT1 has a functional effect on cognitive performance in ADHD.

The results of the current study show that children with ADHD experience difficulty in reorienting attention, indicative of impairment in spatial selection. In the exogenous task, this deficit was evident across SOAs and at longer SOAs for the endogenous task. In both tasks, however, interactions with cue validity were further modified by higher-order effects involving target side. For the exogenous task at the 200-millisecond SOA, cuing costs in the ADHD group,
relative to controls, were greater for left-sided targets. The ability of the current study, relative to past studies, to detect lateralized group differences may be partly attributable to increased trial numbers with an attendant reduction in error variance, exclusion of potentially confounding comorbid reading impairments, and exclusion of trials on which a saccade was made.

Our lateralized results imply dysfunction to the posterior orienting system that is dominant in the right hemisphere and resemble effects reported in patients with lesions to the right parietal cortex. Similarly, our findings of increased cuing costs in children with ADHD at the 800-millisecond SOA, although not lateralized, suggest a sluggish posterior reorienting mechanism in ADHD. Other studies using a variety of selective attention paradigms have also found evidence of left-sided impairment in ADHD, indicative of disruption to right-hemisphere posterior attentional systems. Recent brain imaging work also suggests an important role for the right parietal cortex in both the pathology and clinical outcome associated with ADHD. In the current study, children with ADHD were also slower to reorient attention to endogenously cued targets in the left visual field relative to a valid trial baseline. This finding is comparable with that reported previously in adults with ADHD and may suggest additional involvement of frontostriatal systems implicated in the volitional control of attention. Taken together, the results of the present study suggest a broad disruption to right-hemisphere spatial attention systems in ADHD.

Neuropsychological heterogeneity in ADHD is present across multiple cognitive domains and likely explains the failure of a number of studies to document selective attention deficits in ADHD. We sought to dissect this heterogeneity by asking whether a common haplotype of DAT1 predicted spatial attention deficits in ADHD. At the short (200-millisecond) SOA for the exogenous cuing task, DAT1 haplotype status (2 copies vs <2 copies) accounted for 8.5% variance in cuing costs for left visual field targets. Importantly, however, there was also an interaction between diagnosis and DAT1 haplotype: children with ADHD who were also homozygous for the high-risk DAT1 haplotype had the most significant impairment in reorienting attention overall and in particular to targets in the left visual field (5.8% variance). A similar interaction, albeit of smaller effect size (4.9% variance), was observed for endogenous cuing costs at the longer SOA. This effect size is of similar magnitude to those reported between working memory and COMT genotype (4%), for example. Our findings represent the first evidence, to our knowledge, that a common haplotype of DAT1 is a predictor of neuropsychological heterogeneity in ADHD. The largely intact performance of children with ADHD who were heterozygous for the haplotype may help to explain why previous studies of selective attention in ADHD might have failed to document group differences, particularly in relatively small samples. Although there have been isolated reports that DAT1 variants also influence other cognitive domains, such as vigilance and response time variability, in participants with ADHD, a number of studies have failed to document an effect of DAT1 on neurocognitive function in ADHD when using executive and motoric measures. The current results are, however, consistent with our previous observations in the Irish population that parietal-dependent measures of attentional asymmetry are associated with DAT1 variation and predict stimulant response in ADHD.

The association between DAT1 and spatial selective attention, particularly for the exogenous orienting task, implies dopaminergic modulation of posterior attentional systems, including the parietal cortex. The parietal cortex receives strong dopaminergic input and dopamine transporter immunohistochemistry in the posterior parietal cortex has been reported. Yet our results run counter to work suggesting cholinergic modulation of spatial selective attention. Cholinergic agonists such as nicotine reduce the costs of invalid spatial cues in human subjects and the cholinergic antagonist scopolamine increases cuing costs in nonhuman primates. However, an interaction between these systems seems likely since cholinergic agonists promote dopamine signaling. Furthermore, nicotine may bind to the dopamine transporter, mimicking the effect of methylphenidate and increasing dopamine reuptake. Future studies should therefore investigate this potentially important pharmacological interaction and its effects on spatial selective attention.

Taken together, the results of this study demonstrate that DNA variation in a risk haplotype for ADHD predicts spatial inattention in ADHD. Heterogeneity in the extent of selective attention deficit across individuals with ADHD may reflect, in part, genetic differences.

Submitted for Publication: October 3, 2008; final revision received January 25, 2009; accepted February 23, 2009.

Correspondence: Mark A. Bellgrove, PhD, Queensland Brain Institute, University of Queensland, Brisbane, Queensland, Australia 4072 (m.bellgrove@uq.edu.au).

Financial Disclosure: None reported.

Funding/Support: This work was supported by grants from Science Foundation Ireland and the Health Research Board of Ireland. Dr Chambers was supported by a travel grant from the Australian Academy of Science and is currently supported by a BBSRC David Phillips Fellowship. Dr Bellgrove is currently supported by a Career Development Award from the National Health and...
References


